Velocity of heavy oil sand

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Summary

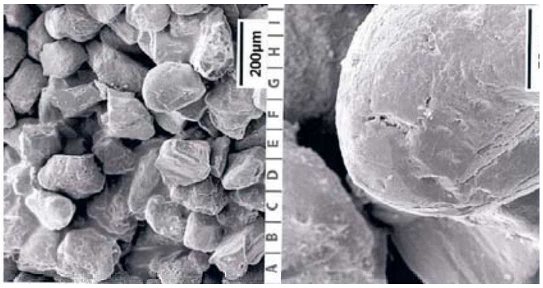
We have measured ultrasonic velocity as a function of temperature for several heavy oil sand samples from shallow depth. Initial measured results suggest that both P- and S-wave velocities of heavy oil sands decrease significantly with increasing temperature. The main contributors to the decrease of velocity are:

1. Transition of heavy oil properties from quasi-solid phase to the liquid phase with decrease modulus.
2. Change in the role of oil in the interaction between heavy oil and sand grains: from as part of the matrix transiting to as a pore fluid.
3. Frequency dependence of these properties.

We have examined the applicability of the Gassmann's equation for the heavy oil saturated samples.

Samples

Several sand samples from shallow heavy oil reservoirs in Alberta, Canada were measured. The samples are loose sands held together by heavy oil from depths between 380 and 500 meters. There is no obvious indication of sample damage by drilling. We observed undisturbed thin shale beds (few mm thick) embedded in sands. We measured the porosity, grain and bulk density of samples at room conditions. Measured data suggest that mineral grain density is around 2.65 gm/cc and porosity ranges from 36 to 40%. The samples show slightly different grain sizes from fine to medium with good sorting. A typical SEM images (Figure 1) show that the sands are clean and well sorted with no cementation. Porosity for the sample is estimated at 37% with permeability of ~7 to 10 Darcy, which is typical for this kind of sands.



ϕ = 37% Perm. ~7 Darcy ρ_g = 2.65 gm/cc

Fig. 1 Oil sand frame

The samples are oil saturated without water, which was dried out. We estimated oil saturation based on measured pore space, bulk density, grain and oil density. Oil saturation for samples is approximately 90%.

Heavy oil properties

We have measured a heavy oil sample with API gravity of 9.2 from one reservoir. Ultrasonic P and S-wave velocities were measured at in-situ pressure and temperature ranges from 0 to 100 ºC as shown in Figure 2. Data shows that

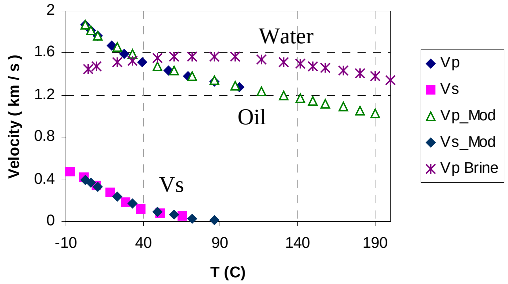


Fig. 2 Measured and modeled velocities of heavy oil and water.

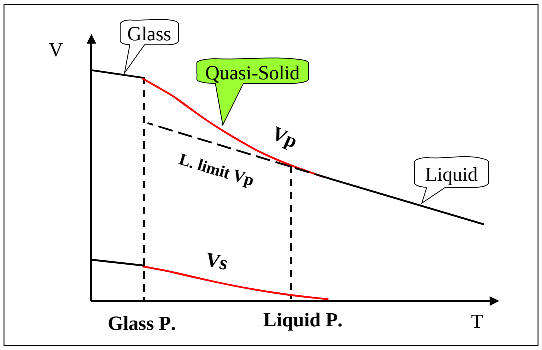


Fig. 3 Schematic of phase change of heavy oil with temperature.

with increasing temperature, both Vp and Vs velocity decreases. In comparison we also show measured brine velocity as function of temperature. As we mentioned (Han, et al, 2006), heavy oil is in quasi-solid phase at in situ conditions. Measured ultrasonic data provide a high bound. With increasing temperature over 70 °C, the heavy oil has transited to liquid phase, Vs approach to zero and negligible, and Vp tends to decrease linearly with increasing temperature. Figure 3 shows the phase change of heavy oil with temperature. We apply the measured oil properties to estimate oil sand properties.

Measurement procedures

In order to simulate in situ steam conditions, we have measured oil sand at in situ differential pressure of 5.6 MPa and temperatures range from 10 to 150 °C to simulate the virgin to the steamed condition. We measured the velocity at "as is" condition, then, saturated the samples with salinity of 14000 ppm of sodium chloride brine, and maintained a constant pore pressure of 2.4 MPa and confining pressure of 8.0 MPa. We monitored the pore volume change during heating processing. After decreasing the temperature to 10 ºC to simulate in situ condition, we increased temperature by 5 to 10 degree increments. We monitored the temperature and pore pressure equilibrium on samples. Fortunately, data measured in short interval at day time and overnight (13-14 hours) show negligible creeping effect on measured data. We assume that the original compaction of oil sands is not damaged. Normally, measuring one sample takes a week.

After taking a measurement at 150 ºC, we performed two tests. First we tested the pore pressure effect. Second, we applied steam flooding to produce heavy oil and measured the velocity change with oil saturation.

Then, we took sample out of vessel and cleaned sample with solvent. We obtained clean, dry sand samples. We measured porosity and grain density, then, Vp and Vs velocity of dry and brine saturated samples at in situ pressure and room temperature.

Velocity as function of temperature

We measured P-wave velocity as a function of temperature on heavy oil sands. A typical data shows interesting feature in Figure 4: velocity first decreases nonlinearly with temperature and then transits into a linear trend to decrease with temperature. We also measured shear velocity as a function of temperature. In Figure 5 a transition point around 60 °C is clearly shown. It is consistent with the measured heavy oil transition point. Compiled P velocity data show a similar pattern (Figure 6) with a slightly different transition point (temperature). Velocity decreases by 30-

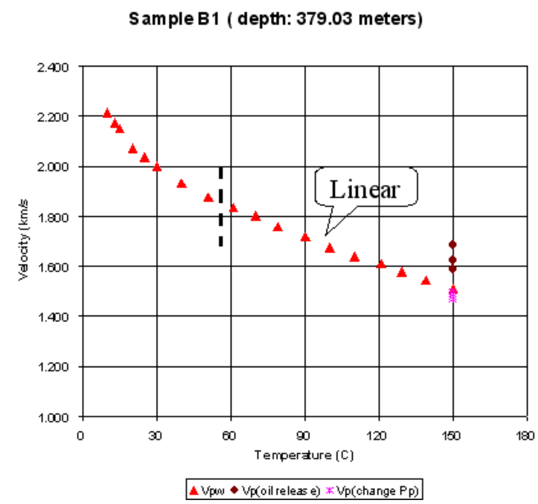


Fig. 4 P- Velocity versus temperature of heavy oil sand

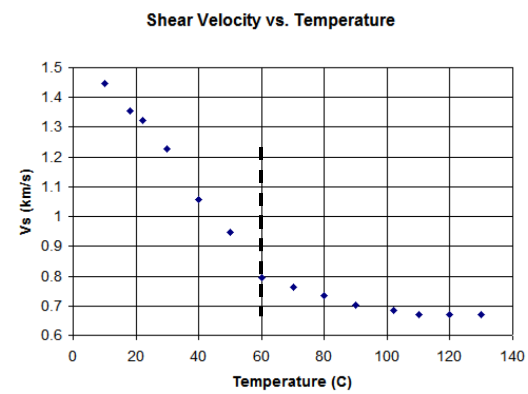


Fig. 5 Shear Velocity versus temperature of heavy oil sand

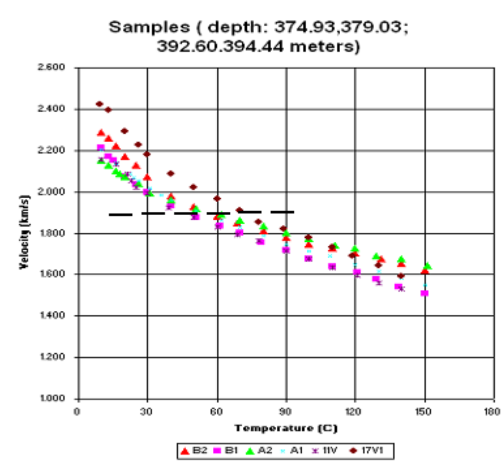


Fig. 6 P- velocity of six heavy oil sand samples

40% as temperature increase from 10 to 150 °C. Different samples had transition points ranging from ~50 °C to 70 °C, which is consistent to the liquid point for heavy oil (Han, et al., 2006). In general, low velocity samples had low transition points. Velocity difference reduced with increase temperature.

Heavy oil saturation effect

We measured velocity with different oil saturation at high temperature. At 150 °C, we produced heavy oil by injecting water and releasing the pressure. As shown in Figure 7, P-wave velocity increased around 10% with increasing water saturation (decreasing oil saturation). The data are consistent with the results of brine saturated sample (Figure 3) and fact that water (brine) has a higher modulus than that of heavy oil at 150 °C.

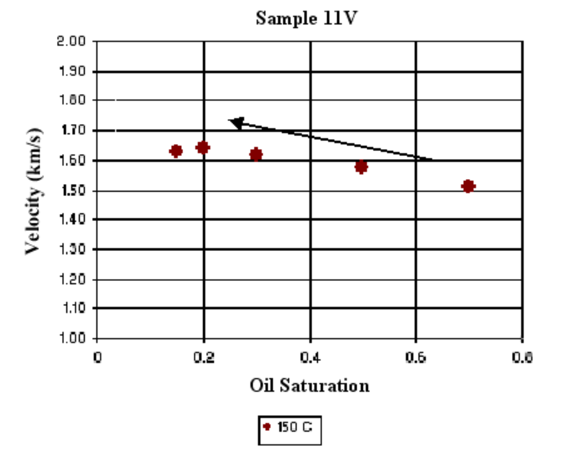


Fig. 7 P- velocity increases with decreasing So

Application of Gassmann's equation to heavy oil sands

We have examined how Gassmann's equation works with heavy oil sands. We assume:

1. Oil properties measured at high frequency can be used.
2. Measured dry velocity at room temperature will remain constant with the applied temperature.
3. We use Gassmann's equation to calculate the velocity at different temperatures with measured oil properties.

Figure 8 shows measured dry and oil saturated P-wave velocities of heavy oil sample. We calculated oil saturated P-wave velocities with the above method. The data show two important features. First, with decreasing temperature from 150 °C to 60 °C, the Gassmann prediction is consistent with the measured data. This means if heavy oil is in the liquid phase with no dispersion, velocity of oil sand also has no dispersion. It also confirms that the liquid point for the heavy oil is around 60 °C. We do not have measured P-wave velocity at high temperature from 150 °C to 200 °C due to limitation of test equipment. But, we can predict P-wave velocity at high temperatures, which shows continue to decrease near linearly. When temperature is below 60 °C, heavy oil is dispersive (Han, et al., 2006) and Gassmann's calculation no longer matches the data, even when we use ultrasonic (high bound) oil properties.

In the Gassmann calculation, we have to maintain a constant shear modulus when fluid properties change with temperature. However, when heavy oils are in the quasi-solid phase, they are no longer a fluid. They become part of rock matrix and cause an increase of the shear rigidity of sands. Calculated shear modulus from measured S-wave velocity and density data (Figure 9) show that at room temperature and in-situ pressure (800

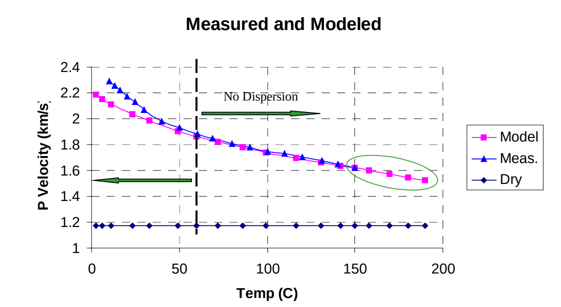


Fig. 8 Measured and calculated P- velocities of oil sands

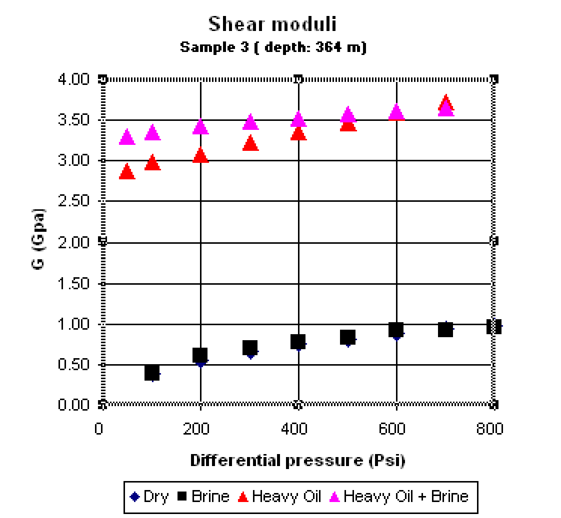


Fig. 9. Calculated shear modulus from measured shear velocity and density at room temperature.

Psi, i.e. 5.6 MPa), the measured shear modulus on clean, dry sample is around 1 Gpa (~Vs = 0.8 km/s). Shear modulus remain unchanged with brine saturation. But with heavy oil saturated state, the shear modulus is higher than 3.5 Gpa (~ Vs = 1.4 km/s). Notice that the shear modulus of the heavy oil itself at this temperature is only < 0.1 Gpa. But the existence of the heavy oil significantly changes the effective shear modulus of the sand oil mixture. Obviously, such significant change of shear modulus cannot be interpreted by any liquid-solid contact model.

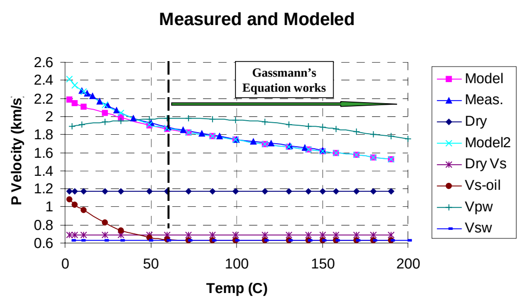


Fig. 10 Calculated P- velocities based on modeled S-velocity.

We attempt to predict the P wave velocity taking into account the variation of shear modulus while keep using the Gassmann equation to calculate the bulk modulus change caused by the oil. It is surprising that we can predict the ultrasonic velocity well at low temperature as shown in Figure 10. For comparison, we also show P-wave and S-wave velocities with water saturation. P-wave velocity is higher than that of oil sands at high temperatures but lower than that of oil sands at low temperatures.

The measured data (ultrasonic) and Gassmann's prediction (low frequency) suggest that the velocity dispersion is limited, and is temperature dependent. For heavier oil or tar, such dispersion can be very significant as suggested by Schmitt (1998).

One of our samples shows an interesting Vp/Vs ratio change with the temperature (Figure 11). The Vp/Vs ratio has its highest value around 40-50 °C, but decreases towards both low and high temperature. To explain this, we notice the heavy oil has an accountable volume expansion with temperature increase. If assuming the pore volume be constant, then the oil pressure has to be raised. When the temperature goes higher from room temperature, pore pressure tends to be higher, sand grain tends to be separated by oil and Vp/Vs ratio increases. Then the heavy oil tends to be less viscous and favor to release the thermal stress, sand grain tends to be packed and Vp/Vs ratio decreases. Such interactive effect with increasing temperature will cause a transition of the Vp/Vs ratio from low to high to low as shown in measured data shown on Figure 11.

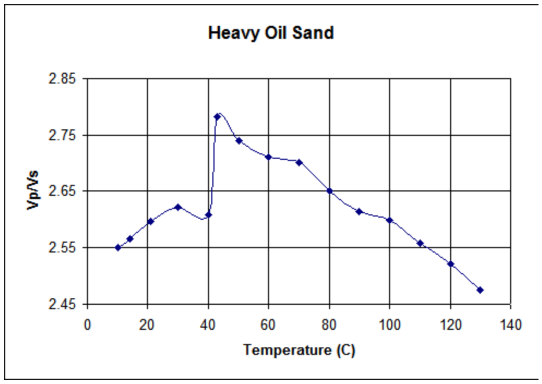


Fig. 11 Vp/Vs ratio change with temperature.

Conclusion

Measured velocity data on heavy oil sands suggest that both P- and S-wave velocity are controlled by oil properties as function of temperature. At temperature higher than the liquid point, heavy oil behaves similar to other light oil. Velocity dispersion appears not significant. At temperature lower than the liquid point, heavy oil is dispersive with high attenuation, so does velocity of heavy oil sands. We can estimate dispersion effect by experimental data and Gassmann's calculation. However, we still have poor understand how heavy oil in the quasi-solid phase interaction with rock frame. Many works have to be done in near future.

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EDITED REFERENCES

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